

Time since prior wildfire affects subsequent fire containment in black spruce

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Abstract. In black spruce forests characterised by high-intensity crown fires, early detection and containment of fires while they are small is crucial for averting progression to fire intensities that exceed suppression capabilities. Fire behaviour conditions encountered during initial attack operations are a key determinant of containment success. Conditions will be controlled in part by stand structural characteristics that can be expected to vary as a fire-origin black spruce (*Picea mariana* (Mill.) B.S.P.) stand ages with increasing time-since-fire. In this study, the influence of time-since-fire on containment outcomes is assessed to explore whether or not prior wildfire exerts a negative feedback on subsequent fires in these ecosystems. Logistic regression analysis using point and polygon fire data for the province of Alberta, Canada, indicated the probability of a containment failure in black spruce increases with time-elapsing since the last fire. Other positive explanatory variables included the size of the fire at the initiation of firefighting and a relative rating of the expected rate of fire spread, the Initial Spread Index (ISI) of the Canadian Forest Fire Weather Index System. Legacy wildfires had a protective effect. When firefighting is initiated at fire sizes ≤ 1 ha, the probability of a containment failure is low during the initial 20–45 years of post-fire stand development, except under the most extreme fire weather conditions.

Additional keywords: Alberta, boreal forest, Canada, crown fires, escaped fire, fine fuels, fire behaviour, fire intensity, fire management, fire suppression, fuel load, fuel management, fuel model, fuel moisture, initial attack, North America, *Picea mariana*, stand-age, surface fuels, time-since-fire.

Received 16 March 2017, accepted 8 August 2017, published online 27 October 2017

Introduction

Stand-age and wildfire activity are inextricably linked in boreal ecosystems. High-intensity, fast-spreading boreal wildfires result in widespread tree mortality and even-aged post-fire regeneration (Heinselman 1981; Van Wagner 1983; Bonan and Shugart 1989). Fire-origin black spruce (*Picea mariana* (Mill.) B.S.P.) stands throughout the boreal are characterised by fire-adapted semi-serotinous cones that support self-replacement successional dynamics with rapid recruitment of a new even-aged cohort of seedlings following fire (Leiffers 1986; Viereck and Johnson 1990; Johnstone *et al.* 2004). Distributions of stand age-classes in crown-fire landscapes have long been used to describe characteristic fire frequencies, given assumptions about whether or not the likelihood of an area burning is independent of stand-age or increasing with time-elapsing since the last fire (Heinselman 1973; Van Wagner 1978; Johnson 1979; Yarie 1981; Johnson and Van Wagner 1985; Johnson and Gutsell 1994). Although it is well recognised that the age of a natural black spruce stand will reflect the time-elapsing since prior wildfire, the extent to which time-since-fire (TSF) influences subsequent fire characteristics is not well understood.

In managed socioecological landscapes like the boreal forest, any negative feedback expressed by prior wildfires on subsequent fires can be expected to interact with efforts by fire

management agencies to arrest and contain fire spread through comparatively transient fire suppression operations. Each year, hundreds of small fires are discovered in black spruce forests in Alberta, Canada, and some of these occur within the boundaries of mapped historical fires. Reported fires receive a response that typically involves ground crews with 4–7 firefighters transported by helicopter with or without supporting tanker aircraft that are dispatched with the objective of initiating firefighting before the fire exceeds 2.0 ha in size. The progress of initial attack efforts to contain fires is well documented in agency fire report records and has been shown to affect area burned in Alberta (Cumming 2005) and Ontario (Martell and Sun 2008).

Fire behaviour conditions encountered during initial attack operations are a key determinant of containment success and will be controlled in part by stand structural characteristics that can be expected to vary within a black spruce stand as it ages. Black spruce forests with continuous vertical and horizontal crown fuels enable easy transition from surface fires to high intensity crown fires, owing to their low canopy base height, high canopy bulk density and low foliar moisture content (Barney *et al.* 1978; Dyrness and Norum 1983; Van Wagner 1977; Van Wagner 1983; Chrosiewicz 1986). Given their propensity to quickly progress to fire intensities that exceed the limits of fire suppression effectiveness, early detection of

fires in black spruce vegetation and containment at small sizes is considered crucial to prevent negative fire effects on people, property and forest values (Martell 2001).

In boreal conifer vegetation, initial attack by firefighters working directly on the fire's edge is highly effective for suppressing slow-moving surface fires with frontal fire intensities less than 500 kW m^{-1} , and will be challenged when surface fire intensities reach $500\text{--}2000 \text{ kW m}^{-1}$, beyond which ground crews are no longer considered effective (Murphy *et al.* 1991; Hirsch *et al.* 1998; Hirsch *et al.* 2004). Fire management agencies in Canada estimate fire intensities in black spruce with the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) using a representative stand condition, the C-2 boreal spruce fuel type, that ignores expected variations in fire intensity at different stages of stand development, particularly during the initial decades of post-fire regeneration.

Following fire, sufficient fuel must accumulate before the site can burn again (Van Wagner 1983) and studies of successional trends in boreal fire activity have consistently concluded there is high fire-resistance during the initial two decades of post-fire stand development. Kiil (1975) estimated that it would take a minimum of 25 years following fire for sufficient accumulation of critical fuels to support moderate fire intensities in black spruce forests of Alberta. Recently burned areas have been associated with reduced fire occurrence in the mixedwood boreal forests of Alberta (Krawchuck *et al.* 2006) and decreased expected fire size in forested areas of Southern Quebec (Marchal *et al.* 2017). These results are consistent with a recent Canada-wide study of fire selectivity for specific forest properties in which Bernier *et al.* (2016) found that fire avoided young (0 to 29-year) stands. The effect of legacy fires on subsequent fire occurrence and fire behaviour in boreal forests over longer time periods of stand development is less clear.

Van Wagner (1983) postulated that fire intensity in boreal conifer vegetation increases rapidly within the first three decades following fire and then decreases to a lower level throughout the mature stage of the stand with a subsequent increase in flammability as the stand eventually deteriorates and regenerates. In boreal ecosystems, variations in fire intensity with age are thought to reflect changes in the quantity, arrangements and availability of fine fuels for combustion rather than the accumulation of surface organic matter or downed woody debris (Van Wagner 1983). The influence of stand-age on fire behaviour in black spruce generally evades direct study due to the wide range of stand ages and associated fire intensities that would require assessment, including fire behaviour conditions that would pose both safety and containment risks.

Data collected during fire management operations provide an imperfect but extensive resource that may provide insight into stand-age and fire behaviour dynamics. Initial attack operations occur over a brief but critical period of time and are documented in detail through reports that record fuel type, fire size and the timing of initial attack activities and milestones. Fire behaviour conditions encountered during initial attack are highly variable among fires and will be dictated by site-specific fire environment variables, including fire weather, fuel moisture and the type and arrangement of fuels, which can be expected to vary as a fire-origin stand ages with increasing time-since-fire.

This study aims to assess whether or not the time elapsed since prior wildfire in black spruce forests has a detectable influence on the probability that initial attack efforts will fail to contain the fire. The time between consecutive fires at the same location was derived from the Government of Alberta's province-wide database of point fire locations using records from the recent historical period (1996–2014) in combination with a provincial polygon database that included historical fire perimeters dating back to 1931. To minimise variations in containment outcomes that can be expected to result from differences in firefighting capability, firefighting effort, forest fuels and ignition type, the assessment was limited to lightning-ignited fires reported in black spruce vegetation within the boundaries of previously burned areas and only included fires that were subject to initial attack while they were small in size ($\leq 2.0 \text{ ha}$). Multiple logistic regression analysis was used to investigate the effect of TSF on the probability of containment failure, in combination with other variables representing fire behaviour conditions and fire management capabilities.

Data and methods

Study area

The area under investigation spanned $393 \times 10^6 \text{ km}^2$ encompassing the forest protection area of the province of Alberta, Canada (Alberta Sustainable Resource Development 2001). Within this area, containment outcomes were evaluated for fires burning in the C-2 Boreal Spruce fuel type of the FBP system. Fires reported in other fuel type classifications were excluded to control for variability in stand dynamics and fire behaviour expected with different vegetation types. The C-2 fuel type consists of moderately well stocked black spruce (*Picea mariana* (Mill.) B.S.P.) stands with a continuous feather moss or *Cladonia* forest floor layer on both upland and lowland sites and excludes sphagnum bogs (Forestry Canada Fire Danger Group 1992).

A total of 530 fires (Fig. 1) were selected for analysis following the process described in detail below. Analysed fires were distributed across eleven different natural subregions in Alberta (Natural Regions Committee 2006) with 84% within the Boreal Forest Region (Table 2). In Alberta, black spruce is common in northern and central regions on poorly drained muskeg areas. Black spruce is a notably important vegetation type in two natural subregions where 66% of analysed fires occurred: the Central Mixedwood subregion, where black spruce stands are common on extensive peatlands; and the Lower Boreal Highlands subregion, where early and to mid-seral pure black spruce forests and open black spruce peatlands are found. Black spruce is also common in the Northern Mixedwood, Upper Boreal Highlands and Upper Foothills subregions.

It is possible that some of the analysed fires that were classified as burning in the C-2 Boreal Spruce fuel type were not actually burning in black spruce vegetation. Pure white spruce (*Picea glauca* (Moench) Voss) forests would be potential candidates for misclassification and are common in the Lower Foothills where 8.3% of the analysed fires occurred. It is assumed that other pure conifer forest types and deciduous-conifer mixed forests in Alberta would have been readily classified into one of the other

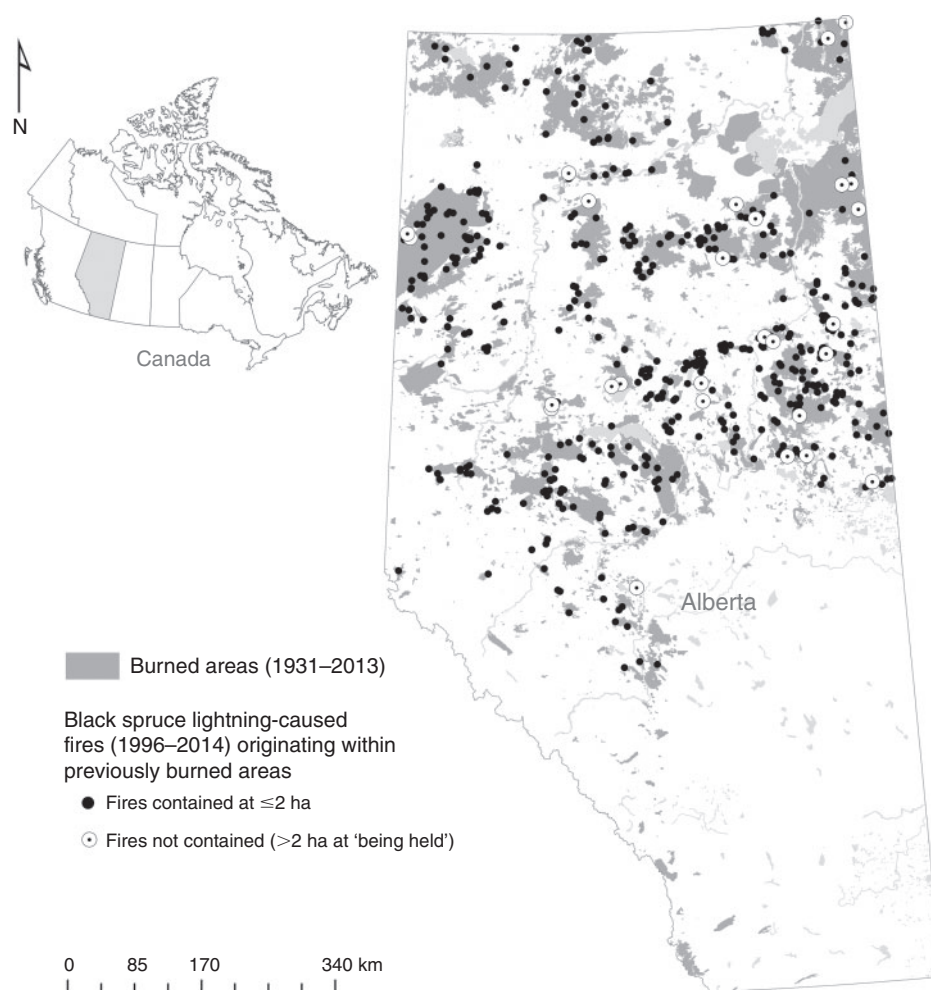


Fig. 1. Locations of lightning-caused fires ($n = 530$) in black spruce fuels within previously burned areas. A fire event was considered within a previously burned area if a 100-m buffer around the point-origin of the fire was wholly within one or more legacy fire polygons that predated the fire. Fire events were classified as contained if the fire did not exceed 2 ha at the 'being held' stage of control.

available FBP system fuel types including C-1 Spruce Lichen Woodland, C-3 Mature Jack or Lodgepole Pine, C-4 Immature Jack or Lodgepole Pine, and M-1 or M-2 Boreal Mixedwood.

Fire data

Province-wide historical fire databases of point fire locations and fire polygons were obtained from the agency responsible for fire management in the province, Alberta Agriculture and Forestry. Analysed fires consisted of point fire locations drawn from an historical wildfire database (Alberta Agriculture and Forestry 2016a) and were restricted to the fairly recent 1996–2014 period to ensure containment outcomes were assessed under consistent fire management policies, operational conditions and record keeping standards. Not all attributes in the point fire database were consistently reported. Point-fire records included in the analysis had complete documentation for the following attributes, which were used to select data and derive variables for analysis: geographic coordinates of the fire origin;

date and time the fire was reported; date and time the fire was first assessed by agency personnel; size of the fire at the initiation of firefighting; size of the fire at the 'being held' stage of control; FBP fuel type classification; and cause of ignition. Point fire data were also available for periods further in the past, which were generally characterised by less detailed reporting practices. Point fire data for the 1961 to 1995 period were only used for supplementary purposes to identify potentially confounding historical fires in a process described in further detail below.

Lightning was responsible for 88% of black spruce fires that occurred in previously burned areas. These lightning-caused fires were analysed separately to control for variability in ignition processes (Wotton and Martell 2005; Beverly and Wotton 2007) and inconsistent response efforts. Response effort varies when human-caused fires are discovered comparatively soon after ignition and exposed to suppression action by observers before the arrival of fire management personnel. Categories of human fire causes (e.g. industrial, resident, recreation) were not analysed because of the limited records

available (≤ 35 per category) and the insufficient number of fires that escaped containment (≤ 4 per category).

Selected point fire data were used in combination with a second database of historical wildfire perimeters (Alberta Agriculture and Forestry 2016b) that documented the spatial extent of all known and mapped historical burned areas in the province. These legacy fire records included documentation of the year of the fire; a classification of the area (i.e. burned area v. interior unburned area); and the source of the fire perimeter (Table 1). Only those portions of legacy fire polygons classified as burned areas were used for time-since-fire calculations. Ignitions occurring in other mapped areas, including unburned residual vegetation patches and all polygons associated with prescribed fires were excluded from the analysis.

TSF calculations

TSF was calculated as the year the point fire occurred minus the year of the legacy fire polygon within which it occurred. Point fire locations were buffered with a 100-m radius and only fires with buffers wholly within previously burned areas were

retained to minimise potential error associated with spatial mapping. In some cases, point fires occurred in areas previously burned by multiple legacy fires. If the 100-m buffer around the analysed fire or portions of it included overlapping burned areas, only the most recent legacy fire year was used in TSF calculations. If the 100-m buffer included abutting adjacent areas burned by historical fires that occurred in different years, TSF was calculated as the area-weighted average of the legacy fire years.

Legacy fire polygons used to calculate TSF were derived from multiple sources with varying levels of spatial detail (Fig. 2). Polygons derived from fire history maps (1 : 500 000) reported in Delisle and Hall (1987) suffered from simplified boundaries and the absence of interior residual vegetation patches. In comparison, fire perimeters derived from aerial photography or hand-sketches had refined perimeter and interior edge details. Underestimates in TSF are possible if analysed fires occurred in unmapped unburned residual areas within legacy fire perimeters. These residuals can occupy as much as 25% of the area contained within a boreal fire perimeter (Andison 2012; Araya et al. 2016). One means of reducing potential inaccuracies in TSF calculations due to unrefined perimeter detail is to limit calculations to polygons from the post-1951 period during which simplified fire history maps were responsible for just 13% of legacy fire perimeters (Table 1). Probability of containment failure was assessed for the full dataset and this post-1951 subset.

A more concerning data limitation is the possibility that an unmapped wildfire disturbance affected the area at some point in time between the two fire dates used to calculate TSF. This would result in an overestimate of TSF and could potentially inflate a positive relationship between TSF and the probability of a fire escaping containment. To identify fires that were vulnerable to TSF inaccuracies from potentially confounding unmapped legacy fires, provincial records of point fire locations dating back to 1961 were used. These point fire records documented the final size of each fire, but supplied no information about their shape or orientation in relation to the 100-m buffers used to calculate TSF. To evaluate whether or not a potentially confounding fire was of a sufficient size and

Table 1. Proportion of time-since-fire values by source of historical wildfire polygons for the full dataset and subset of post-1951 polygons
All data includes polygon records with years ranging from 1938 to 2012. Post-1951 subset includes polygon records with years ranging from 1952 to 2012. GPS, global positioning system; IR, infrared

Source	All data	Post-1951 subset
1 : 500 000 fire history maps ^A	0.44	0.13
Digitised from aerial photo	0.39	0.67
Non-corrected airborne GPS	0.06	0.09
Non-corrected ground GPS	0.05	0.05
Historical fire source unknown	0.03	0.02
1 : 250 000 scale Fire Incidence Map	0.01	0.03
Hand sketch of any type	0.01	0.01
Corrected airborne GPS	<0.01	0.01
Processed IR scan image	<0.01	0.01

^ADelisle and Hall (1987).

Table 2. Frequency of analysed fires by Natural Subregion and containment outcome

Natural subregion	Count of fires			Percentage of fires (%)
	Contained	Not contained	Total	
Central Mixedwood	220	13	233	44
Lower Boreal Highlands	128	4	132	25
Lower Foothills	44	—	44	8
Dry Mixedwood	32	3	35	7
Upper Boreal Highlands	28	3	31	6
Northern Mixedwood	18	—	18	3
Boreal Subarctic	11	—	11	2
Athabasca Plain	8	2	10	2
Upper Foothills	8	—	8	2
Kazan Uplands	5	2	7	1
Subalpine	1	—	1	0
Total	503	27	530	100

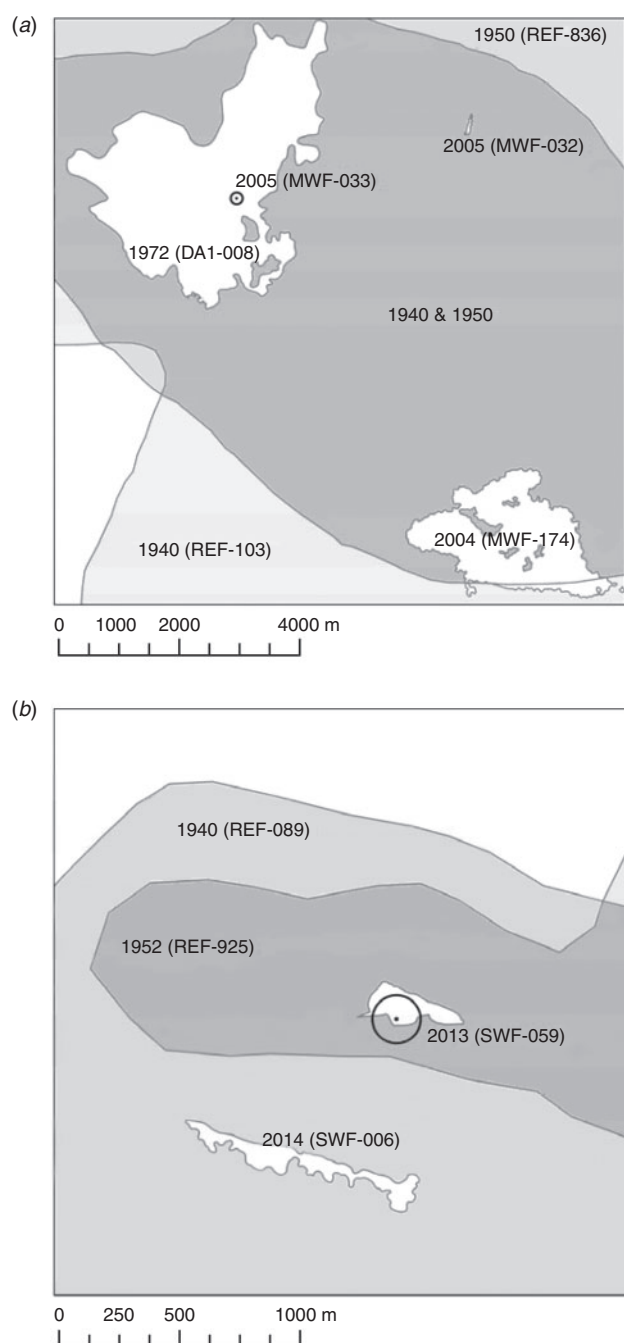


Fig. 2. Variations in perimeter and interior edge detail by source of legacy fire polygons. Analysed fires (a) MWF-033, 2005 and (b) SWF-059, 2013 and associated 100-m buffers are shown for reference. Historical polygon sources were: 1 : 500 000 fire history maps – 1940 (REF-103, REF-089), 1950 (REF-836), 1952 (REF-925); digitised from aerial photo – 1972 (DA1-008), 2004 (MWF-174), 2014 (SWF-006); and hand-sketched – 2005 (MWF-032).

proximity to burn into any of the TSF buffers, a simple fire growth model was used.

For each point fire location for which TSF was derived, the distance to potential confounding fires within 10 km was also calculated. The critical fire size that the potentially confounding

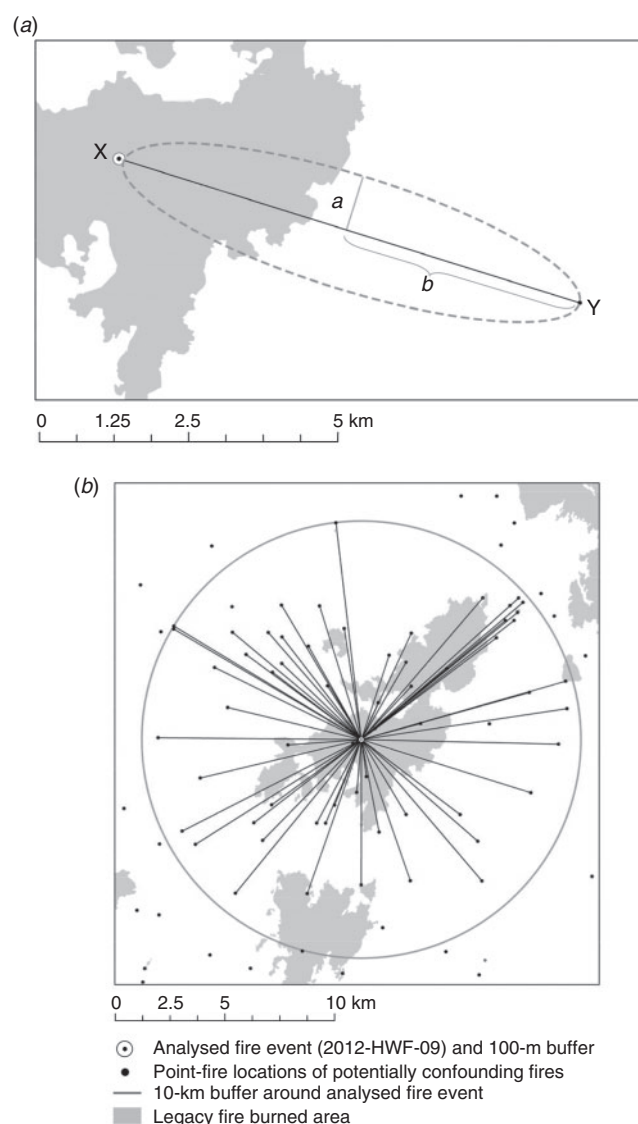


Fig. 3. Illustrative examples of fire pathways assessed between an analysed fire and potentially confounding fires that occurred within 10 km. (a) Distance between analysed fire 'X' and potentially confounding fire 'Y' is 8094 m. With a length to breadth ratio of 4:1, the critical size needed for fire 'Y' to burn into the 100-m buffer around fire 'X' is 1255 ha, calculated as $\pi \cdot a \cdot b$ and denoted by the elliptical area shown (dotted line). At 0.6 ha, fire 'Y' did not achieve the critical size. (b) Multiple pathways assessed for fire 2012-HWF-109. Not all fires within the 10-km buffer have a pathway connecting it to the analysed fire event. This occurs when the date of the surrounding fire did not fall between the dates of the two fires used to calculate time-since-fire.

fire would need to achieve to spread into the TSF buffer was estimated assuming a direct path between the two fires and elliptical fire spread with a length to breadth ratio of 4:1, representative of a worst-case scenario (Fig. 3a). The critical fire size was then compared with the reported fire size to identify any potentially confounding fires that achieved sizes sufficient to affect a 100-m buffer used in TSF calculations.

An example of the multiple fire pathways assessed between TSF buffers and potentially confounding surrounding fires is

shown in Fig. 3b. Evaluations of over 18 000 fire pathways between TSF buffers and surrounding point fire locations indicated that only 27 fires (<5%) used in TSF calculations were vulnerable to potential TSF inaccuracies due to nearby known but unmapped fires that had potential to burn-over all or part of their 100-m buffer. These 27 fires were removed from further analysis, but did not eliminate the possibility of unknown, unmapped fires affecting remaining fire buffers used in TSF calculations. Unknown fires must escape detection and this would most commonly occur when fires achieve small sizes with limited potential to influence surrounding areas.

Omissions of large fires is less likely but possible, especially during the earliest decades of provincial record keeping. Prior to 1952, Alberta's fire exclusion policy involved fighting only those fires within 16 km of roads and major waterways (Alberta Sustainable Resource Development 2001) and comprehensive mapping of even large fires is unlikely. Policy changes introduced in 1952 served to expand fire suppression efforts in the province as a result of extreme timber losses associated with the Chinchaga fire (Tymstra 2015) and would have had similar implications for fire documentation and mapping efforts. Potential error in TSF calculations due to unknown, unmapped fires was controlled for, in part, by assessing containment outcomes for the post-1951 subset of the data, during which perimeter mapping of legacy fires was also more refined.

It is unlikely, but possible, that harvesting activities affected areas contained within the 100-m buffers around the analysed fires due to the limited time available for the forest to develop between the two fires. Legacy fires used for TSF calculations occurred, at most, 74 years before the subsequent fire that was assessed and 62 years when the data were restricted to the post-1951 subset. In merchantable black spruce areas, the economic rotation age would occur later; for example Benson (1973) identified the economic rotation age for black spruce at 75–129 years.

Fire behaviour conditions

Fire behaviour during containment efforts regulates fire suppression effectiveness (Murphy *et al.* 1991; Hirsch *et al.* 1998). Canadian Forest Fire Weather Index (FWI) system (Van Wagner 1987) components calculated from fire weather observations on the day the fire was reported were used to infer fuel moisture and fire behaviour conditions at the time of initial attack. Each point fire record was assigned a daily fire weather record taken from the nearest available Government of Alberta weather station identified from a province-wide network of fire weather stations in operation for various durations and time periods. Almost all analysed point fires (98%) were matched with weather records taken from stations located within 50 km of the fire location and approximately half (48%) were within 20 km. Fire weather records included noon (1200 hours LST) measurements of dry bulb temperature, relative humidity, 10-m open wind speed, and precipitation, as well as calculated components of the FWI system. The FWI system contains three fuel moisture codes that track daily fluctuations in the fuel moisture content of ground fuels layered at increasing forest floor depths. These moisture codes are used to derive three relative daily ratings of fire behaviour potential representing fire intensity,

spread rate and fuel consumption (Van Wagner 1987). All six FWI system components were included in the analysis: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Buildup Index (BUI) and the Fire Weather Index (FWI).

Fire response capability

Three variables were evaluated as indicators of response capability: size of the fire at initial attack, response time, and provincial fire load. The size of a fire at the initiation of firefighting is an important determinant of containment success in the boreal forests of Alberta (Arienti *et al.* 2006) and was included as a general indicator of the level of response. Fire growth before the onset of firefighting can be expected to increase as a result of limitations in fire response capability. This can occur when a fire eludes detection for extended durations or the response to the fire is delayed once reported.

To account for variations in fire response capability that may have influenced fire containment outcomes, fire response time was calculated for each analysed fire as the number of minutes elapsed between the time the fire was reported and the time it was assessed by agency personnel. Fire response capability can also be expected to decline as the operational load managed by the agency increases. Fire load was defined as the count of fires reported in the province on the day of the fire and up to 9 days prior. Four fire load variables were calculated for each fire consisting of 1-, 3-, 5- and 10-day windows ending and inclusive of the day the fire was reported.

The precise nature of the initial attack response that each fire was subjected to once firefighting was initiated could not be determined from the available agency records. Some fires may have only received suppression from ground crews with helicopter bucket support to provide water, whereas others may have received a response from ground crews in combination with air tankers dropping water or retardant. Although the mix of resources used in initial attack can vary from fire to fire, it is assumed that all fires received a consistent response given fire behaviour conditions. Under this assumption, variations in initial attack methods would be represented by other variables included in model building (e.g. the size of the fire at the onset of firefighting and FWI system components representing potential fire behaviour).

Statistical analysis

A binary containment outcome (failure or success) was derived for each fire based on fire size at the 'being held' stage of control. A fire is deemed as 'being held' when fire growth past expected boundaries is not anticipated given current weather conditions and resources, and the fire perimeter remains within pre-determined boundaries (Canadian Interagency Forest Fire Centre 2003). A containment failure was defined as a fire that exceeded 2.0 ha in size before it was contained, despite the initiation of firefighting while it was ≤ 2.0 ha. The Government of Alberta has a provincial strategy of initiating firefighting on newly discovered fires before they exceed two hectares in size (Alberta Agriculture and Forestry 2017) and containment outcomes were only assessed for fires that received this successful initial attack response. Wilcoxon rank sum and χ^2 tests were

used to assess differences between containment outcomes for TSF and other explanatory variables representing fire behaviour conditions and response capabilities. Multiple logistic regression was used to model the probability of initial attack containment failure:

$$P(cf) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \dots + \beta_n x_n)}} \quad (1)$$

where $P(cf)$ is the probability of a containment failure, x_{1-n} are the independent variables, and β_{1-n} are regression coefficients. The probability of containment was modelled as a function of independent variables that included time-since-fire and variables representing fire behaviour conditions and fire response capabilities. Maximum likelihood estimates of model parameters were computed in a generalised linear model framework using R (R Core Team 2016). Pairwise collinearity of covariates was assessed with the Spearman correlation coefficient. Linearity between the logit of the response and the explanatory variables was assessed graphically. Model selection was based on Akaike's information criterion (AIC) and model predictive ability and goodness of fit was assessed by the likelihood ratio χ^2 test, the Wald χ^2 test for individual parameters, and Nagelkerke's pseudo R^2 . Classification quality of the model was evaluated with the C statistic, which is equivalent to the area under the Receiver Operating Characteristic (ROC) curve. ROC values range from 0.5 to 1, with minimum thresholds of 0.7 and 0.8 corresponding to acceptable and excellent model discrimination respectively (Hosmer and Lemeshow 2000). Models were formulated to identify the most parsimonious combination of predictor variables drawn from each of the three groupings of independent variables representing time-since-fire, fire behaviour conditions and response capability. Bootstrapping was used for internal validation of the model. Difference between original and bias-corrected indices of predictive accuracy were used to assess how well the predictions were calibrated and the overall reliability of the model.

Estimation and results

Initial attack resulted in successful containment of 95% of small (≤ 2.0 ha) lightning-ignited fires burning in black spruce vegetation within previously burned areas and this was consistent for both the full dataset and the post-1951 subset of the data. Average TSF was shorter for fires that were contained in comparison with those that were not. This difference was strongly significant for the post-1951 subset of the data ($n = 267$) where average TSF was 26 years for contained fires and 37 years for fires that escaped containment (Table 3). The shortest TSF value associated with a fire that escaped containment was 17 years. This was not due to a lack of fires during early post-fire stand development. Seventy-eight of the analysed fires, equal to 15% of the data, had TSF values < 17 years. The size of the fire at the onset of firefighting was significantly different between containment outcomes for both the full dataset and the post-1951 subset. Differences in FWI system components between the two containment outcomes were not significant when comparing proportions of values in the high or extreme range (Table 4). None of the fire load variables or the response time variable were significantly different between containment outcomes.

Many of the FWI system components were correlated including strong correlations between: ISI and FFMFC; and among FFMFC, DMC, DC, BUI and FWI. All of the fire load variables were strongly correlated with each other. Response time, TSF and size of the fire at the onset of firefighting were not highly correlated with any other independent variables. To ensure that multiple collinearity would not affect the analysis, only combinations of variables with pairwise Spearman coefficients r within $-0.5 < r < +0.5$ were included in model building. The selected best model for predicting the probability of a containment failure, based on AIC, included the same three parameters for both the full dataset and the post-1951 subset (Eqn 2):

$$P(cf) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 SIZE + \beta_2 ISI + \beta_3 TSF)}} \quad (2)$$

where $P(cf)$ is the probability of a containment failure, β_{0-3} are regression coefficients, $SIZE$ is the size of the fire at the onset of firefighting, ISI is the ISI of the FWI system, and TSF is the time-elapsed since the last fire. There was no support for alternate models that included combinations of response time, fire load variables and other FWI system components. The coefficients of $SIZE$ ($P < 0.0001$), ISI ($P < 0.01$, $P < 0.05$) and TSF ($P < 0.05$, $P < 0.01$) were all significant for both the full dataset and post-1951 subset, and the signs were positive as expected (Table 5). The R^2 values for the models were 0.35 and 0.54 for the full dataset and post-1951 subset respectively.

The number of events per predictor variable (EPV) can affect confidence interval coverage, Type-I error and relative bias in binary logistic regression models. These issues are uncommon with EPV of 5–9 (Vittinghoff and McCulloch 2007). Selected models had EPV of 9.0 and 4.7 respectively and were further assessed with comparisons of original and bias-corrected measures of model accuracy through bootstrap validation, which indicated no biases in the estimates. Bias-corrected R^2 values (0.33 and 0.48) confirmed there was no overfitting in the original model. Somer's D original and bias-corrected values were 0.85 and 0.82 for the full dataset and 0.91 and 0.88 for the post-1951 subset. The C statistic indicated both models were strong with 92% concordance between predicted probabilities and observed outcomes for the full dataset and 96% for the post-1951 subset.

TSF was marginally significant for the full dataset ($P < 0.05$) and significance increased ($P < 0.01$) when data were restricted to the post-1951 period. Legacy fire polygons were of an overall higher quality and completeness during the post-1951 period and TSF values were less likely affected by unmapped legacy fires and unmapped residual vegetation patches within legacy fire perimeters. The moderating influence of TSF comes to bear most strikingly on fires burning under fuel and weather conditions that support rapid fire spread, but are subject to the initiation of firefighting efforts before approaching the escaped-fire size limit. When firefighting is initiated at a fire size of 0.5 to 1.0 ha with ISI values that are not extreme (i.e. ≤ 15), the probability of a containment failure is low and fairly unresponsive to increasing TSF until 20 to 45 years post-fire, after which the probability of a containment failure increases rapidly with increasing TSF. Fig. 4 illustrates this pattern for the case where fire size at the initiation of firefighting ($SIZE$) is 1.0 ha, given the model parameters

Table 3. Basic descriptive statistics for continuous explanatory variables used in logistic regression modelling, by containment outcome for (a) the full dataset and (b) the post-1951 subset

(a) Full dataset	Contained (<i>n</i> = 503)				Not contained (<i>n</i> = 27)			
	Mean	Median	s.d.	Range	Mean	Median	s.d.	Range
Size at initiation of firefighting (ha)	0.26 ^A	0.1	0.41	0.01–2.0	1.13 ^A	1	0.71	0.01–2.0
Time-since-fire (years)	42.71	51	21.3	1–74	48.52	57	17	17–68
Response time (minutes)	74.23	22	33.53	0–1532	83.07	14	328.99	1–1727
1-day fire load	35.27	24	29.01	1–135	29.22	20	23.93	5–86
3-day fire load	73.14	60	52.35	3–248	73.81	79	49	14–167
5-day fire load	98.39	89	67.22	3–302	99.44	100	61.71	21–227
10-day fire load	147.7	133	91.09	8–456	151.3	152	66.04	37–318
(b) Post-1951 subset	Contained (<i>n</i> = 253)				Not contained (<i>n</i> = 14)			
	Mean	Median	s.d.	Range	Mean	Median	s.d.	Range
Size at initiation of firefighting (ha)	0.27 ^A	0.01	0.42	0.01–2.0	1.30 ^A	1.5	0.58	0.02–2
Time-since-fire (years)	26.00 ^B	25	17.4	1–62	36.99 ^B	28.5	16.26	17–61
Response time (minutes)	61.77	22	189.68	0–1532	17.29	14	13.1	1–47
1-day fire load (count)	35.94	24	30.06	1–135	21.79	15.5	16.46	7–60
3-day fire load (count)	76.64	62	54.72	3–248	61.21	59	37.08	15–120
5-day fire load (count)	105	89	72.6	3–302	91.4	83	58.91	22–189
10-day fire load (count)	154.3	136	97.29	8–456	152.2	153	75.26	37–318

^ASignificantly different between the two containment outcomes (Wilcoxon rank sum test, $P = <0.0001$).

^BSignificantly different between the two containment outcomes (Wilcoxon rank sum test, $P = 0.03$). All other variables were not significantly different between the two containment outcomes (Wilcoxon rank sum test, $P > 0.05$).

Table 4. Proportion of Fire Weather Index (FWI) system values in the high or extreme range by containment outcome for (a) the full dataset and (b) the post-1951 subset

High or extreme values were classified as follows: FPMC, Fine Fuel Moisture Code >88 ; DMC, Duff Moisture Code >40 ; DC, Drought Code >300 ; BUI, Buildup Index >60 ; ISI, Initial Spread Index >10 ; FWI, Fire Weather Index >20 . There were no significant differences between the two containment outcomes (χ^2 , 1 d.f., $P > 0.05$).

	(a) Full dataset				(b) Post-1951 subset			
	Contained (<i>n</i> = 503)		Not contained (<i>n</i> = 27)		Contained (<i>n</i> = 253)		Not contained (<i>n</i> = 14)	
	Proportion	Count	Proportion	Count	Proportion	Count	Proportion	Count
FFMC	0.48	239	0.52	14	0.53	133	0.43	6
DMC	0.32	159	0.41	11	0.38	97	0.43	6
DC	0.51	256	0.56	15	0.53	135	0.57	8
ISI	0.12	60	0.26	7	0.13	32	0.14	2
BUI	0.30	153	0.33	9	0.35	88	0.36	5
FWI	0.13	64	0.26	7	0.27	69	0.21	3

Table 5. Maximum likelihood estimates, standard errors and P -values for each term included in the selected model for (a) the full dataset and (b) the post-1951 subset

Term	(a) Full dataset			(b) Post-1951 subset		
	B	s.e.	P	β	s.e.	P
Intercept	−6.7761	0.9746	<0.0001	−10.36	2.34	<0.0001
SIZE	2.4144	0.341	<0.0001	3.78	0.83	<0.0001
ISI	0.1186	0.038	0.0018	0.15	0.06	0.0151
TSF	0.0341	0.0139	0.0143	0.10	0.03	0.0026

estimated for the post-1951 subset of the data shown in Table 5. With an ISI of 10 and SIZE of 1.0 ha, the probability of a containment failure increases almost 3-fold from 0.25 to 0.72 as TSF is increased from 40 to 60 years. These results are consistent with expectations. Fires burning under low to moderate FWI system values (i.e. ISI <5) will grow slowly and are easily suppressed, regardless of structural variations in the fuel complex. At the other extreme, onset of firefighting as a fire approaches 2.0 ha will increase the likelihood of the fire exceeding 2.0 ha irrespective of fuel structural variations.

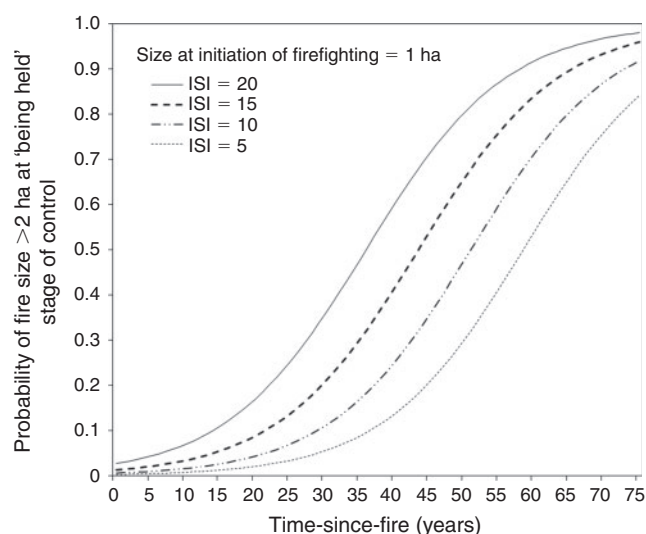


Fig. 4. Probability that fire size will exceed 2 ha at the 'being held' stage of control as a function of time-since-fire (TSF) for Initial Spread Index (ISI) values of 5 through 20 in intervals of 5, assuming the fire was 1 ha at the initiation of firefighting activities.

Discussion

Time-elapsed since the last fire had a significant effect on the containment outcomes of subsequent fires burning in black spruce vegetation during the first 75 years following the legacy fire. The significant positive effect of TSF on the probability that a new fire would exceed 2.0 ha at the 'being held' stage of control was detected in combination with two other drivers of containment outcomes that were identified by [Arienti et al. \(2006\)](#) for a boreal mixedwood forest in north-eastern Alberta: the size of the fire at the onset of firefighting and a measure of fire behaviour conditions represented by the ISI of the FWI system. [Podur and Martell \(2007\)](#) also found that ISI is a good predictor of the probability of a fire escaping suppression in Ontario.

The results of this study suggest that in black spruce forests of Alberta, Canada, prior wildfire may have a protective effect for 20 to 45 years during which the probability of a new fire escaping containment within a legacy fire perimeter is low, except under the most extreme fire behaviour conditions. Beyond the early decades of stand development, the probability of a containment failure increases rapidly with TSF. These results are consistent with the three fuel successional phases identified by [Cronan and Jandt \(2008\)](#) in a study of fire behaviour and succession in black spruce forests of interior Alaska, based on fuel load measurements and fire behaviour models: a fuel-limited pioneer phase (<20 years) that supports low-intensity surface fire; a transition phase (20–45 years) with increasing fire spread rates with stand age but limited fuel loads that inhibit fire intensity and crown fire development; and the forested phase (>45 years) characterised by high intensity crown fires predicted under high-severity fire weather conditions.

Similar trends in predicted fire behaviour and stand age have been reported for Scots pine (*Pinus sylvestris* L.) boreal forests in Sweden ([Schimmel and Granström 1997](#)) and jack pine

(*Pinus banksiana* Lamb.) stands with black spruce understory in boreal Canada ([Lavoie 2004](#)). [Bessie and Johnson \(1995\)](#) concluded that fuel variables and modelled crown fire behaviour were unrelated to stand age for upland sub-alpine conifer forests of the Canadian Rocky Mountains, although a pattern of increasing potential surface fire intensity was suggested during early stand development. In contrast, [Johnston et al. \(2015\)](#) found that increases in crown fuel load and crown bulk density over time suggested that the risk of crown fire and potential crown fire intensity increases continuously with stand age for a post-fire chronosequence of forested boreal spruce bog in central Alberta.

If fire intensity is age-dependent in black spruce stands, then initial attack response to fires in older stands within Alberta will involve comparatively higher fire intensities relative to those experienced in younger stands burning under otherwise identical conditions. Higher fire intensities and faster rates of spread will slow initial attack progress and increase the likelihood that a fire grows beyond 2.0 ha. It is also possible that changes in stand structural characteristics with age inhibit the physical movement of ground crews or effectiveness of helicopter bucketing and air tanker drops either alone or in combination with escalated fire behaviour. The precise underlying mechanism by which TSF influences containment failure in black spruce cannot be determined from the results of this study and will require further investigation, possibly through experimental fires in black spruce stands with varying TSF or through analysis of stand structural characteristics across a TSF chronosequence in combination with physical process-based modelling of fire behaviour. Age-dependent fire intensity in black spruce stands with very long TSF values (>75 years) were not addressed by this study and requires further research, as does assessment of these relationships in black spruce forests of eastern Canada.

The results of this study may be informative for fuel management planning in the province of Alberta. Conversion of fuels to less-flammable types with lower rates of spread is one of three main options for fuel management in boreal forests, the others being fuel reduction and fuel isolation ([Pyne et al. 1996](#); [Amiro et al. 2001](#); [Girardin and Terrier 2015](#)). The pattern of different stand-ages, burned areas and unburned patches across a landscape creates heterogeneity that influences subsequent fire behaviour ([Turner and Romme 1994](#); [Amiro et al. 2001](#); [Peterson 2002](#); [Chapin et al. 2008](#)) and fire size distributions ([Cui and Perera 2008](#); [Kitzberger et al. 2012](#)). In crown-fire ecosystems, it is thought that homogenised stand structures, and the continuous fuel complex that results, enables individual fires to attain larger sizes than would have otherwise occurred had the fire encountered a moderating change in stand structural characteristics. If there is a successional trend in fire behaviour in black spruce forests, management of stand age-classes may represent a means of introducing these moderating stand structural characteristics. Management of age-classes for fire containment objectives would necessitate consideration of a diverse range of complex interactions including climate change, harvesting and biodiversity conservation objectives (e.g. [Cyr et al. 2009](#); [Boulanger et al. 2017](#)).

The protective effect of prior wildfire found in this study is generally consistent with several recent studies in the United States, Australia and Europe. Studies that evaluate legacy fire

effects from the apposition of historical fire boundaries have reported that recently burned areas are effective at stopping fires in the tropical savannahs of northern Australia (Price *et al.* 2014) and the western United States (Parks *et al.* 2015). Recognising the coupled interaction between fire suppression activities and fire growth, Thompson *et al.* (2016) reported that previous large fires had a significant and positive effect on suppression effectiveness and fire containment for a case-study fire in New Mexico. In a regional-scale analysis of area burned response to previous fire, Price *et al.* (2015) reported that burned area was influenced by past fire in selected biomes investigated (i.e. Portugal and Australia) but found no such effect in Alberta provincial area burned data for the 1991–2010 period, which suggests the scale of analysis is an important factor in identifying these relationships.

Analysis of fire processes in boreal crown-fire ecosystems is complicated by the safety and containment risks posed by high-intensity fires. In this study, the influence of prior wildfire on containment outcomes was detected using government records that documented the progress of initial attack efforts to contain small fires burning within legacy fire perimeters. This result is surprising given the highly imperfect nature of both the fire report records and historical fire perimeter data used in the analysis and demonstrates that information collected during fire management operations represent a valuable data source for informing our understanding of fundamental ecological processes in boreal forest ecosystems.

Conflicts of interest

The author declares that they have no conflicts of interest.

Acknowledgements

The author thanks B. M. Wotton, M. D. Flannigan, M. E. Alexander, two anonymous reviewers, and the Associate Editor for providing helpful comments on an earlier version of the manuscript.

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